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REPORT

A variable-standards camera and its use to investigate the parameters of an HDTV studio standard

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A VARIABLE-STANDARDS CAMERA AND ITS USE TO INVESTIGATE THE PARAMETERS OF AN HDTV STUDIO STANDARD

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Summary

A broadcast quality camera has been modified so that its field scan can be driven from an external source. With associated field stores to redistribute the video so generated both in time and in space, it has proved possible to investigate a wide variety of parameters that will affect the choice of a future HDTV studio standard. Such a choice should be made not only to produce high quality video in its own right, but also video that is capable of undergoing many forms of conversion to different transmission formats.

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A VARIABLE-STANDARDS CAMERA AND ITS USE TO INVESTIGATE THE PARAMETERS OF AN HDTV STUDIO STANDARD

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1. INTRODUCTION

There is currently much interest in establishing a television standard suitable for domestic displays substantially larger than the 22 to 26 inch diagonal receivers popular today. Typically, display sizes of 1 metre, or about 40 inch, diagonal are assumed[1]. Such displays will be viewed at distances of about 3 times picture height, provided that current living room layouts remain unaltered; this allows the viewer to gain a greater sense of involvement in the action, and gives television more of the impact of motion picture cinemas[2].

Conventional television broadcasting uses one of two standards. In Europe the standard is 625 lines interlaced at a field rate of 50 Hz, while in America and Japan it is 525 lines, also interlaced, at a field rate of 60 Hz. These standards are intended for display on small screens of moderate brightness and are not capable of the performance required for the larger screens of the future. In order to overcome this problem, new television systems, having a higher number of scanning lines and a wider bandwidth, are required. One of the leaders in the study of such high-definition television (HDTV) systems is NHK, the Japanese Broadcasting Corporation. Their investigations into the psycho-visual requirements of HDTV started in 1968 and led to their proposing a standard of 1125 lines interlaced, at a field rate of 60 Hz in 1982[2]. This standard would give approximately double the vertical and horizontal resolution of the conventional 625 and 525-line systems; at the same time, the opportunity was taken to increase the aspect ratio to 5:3, since subjective tests had shown this to be preferable to the current value of 4:3 in domestic receivers. No improvement in movement resolution was considered necessary relative to existing television systems. The 60 Hz field rate gives a much finer temporal sampling interval than the 24 Hz of motion picture film; thus television is better suited than film to the portrayal of close, fast action. Hopefully, the advent of HDTV should allow the advantages of existing television and film systems to be combined.

It was recognised from the outset that, if an HDTV standard could be adopted uniformly throughout the world, significant benefits in equipment availability and ease of programme exchange would result[2]. However a choice of 60 Hz for the field rate potentially does cause problems in those countries that at present have 50 Hz field-rate television standards (Europe, Australia, Russia, China and many other parts of the world, accounting for over 75% of the global population). In Europe, study of these problems has been co-ordinated by EBU Specialist Group V1/HDTV, established in 1982. This group recognised the possible existence of separate, but related, standards in the production, distribution and emission stages of the HDTV programme chain and identified the production standard as being that which needed finalising with the greatest urgency. As a contribution to the activities of V1/HDTV, the BBC has been conducting a series of experiments to investigate the factors affecting the choice of such a production standard; this Report describes the equipment used to conduct some of these experiments and outlines the results achieved.

The concept behind these experiments has been that programmes originated in an HDTV standard should be capable of distribution on as wide a variety of media as possible. This will include broadcasting via conventional 525- or 625-line television services and the conversion to motion-picture film for theatre release, as well as any HDTV broadcasting or cable distribution service. Working on the brief from the EBU working group, the long held use of a single video format between source and display disappears. It is then up to the engineer to design a new, clean video 'packet' that satisfies predicted as well as current repacking requirements, but also with a view to keeping faith with existing facilities. This 'cleanliness' is obtained by having the studio source standard, to a practical level, free from 'aliasing' which may not be objectionable in its own right, but which may present problems to downstream conversion and manipulation processes. For example, present day standards converters using multi-tap spatio-temporal interpolation can produce objectionable artefacts in the presence of modest motion. Consequently one of the major factors that has been investigated is the quality that might be expected after conversion of the HDTV signal to 625/50 or 525/60; the conversion quality to motion picture film has also been studied. In addition the effect of some of the scanning parameters on the resolution, movement portrayal and susceptibility to lighting flicker of the HDTV standard itself has been investigated. Each of these factors is considered separately.

2. EXPERIMENTAL EQUIPMENT

At the time that the work described in this Report was started, it was not easy to obtain an HDTV camera and display equipment, so it was decided not to attempt to produce a true HDTV picture. Instead, conventional 625-line equipment was modified so that it could simulate a portion of such an HDTV scene; this approach had been used in the past and found to be very successful[3]. A block diagram of this simulation equipment is shown in Fig.1.

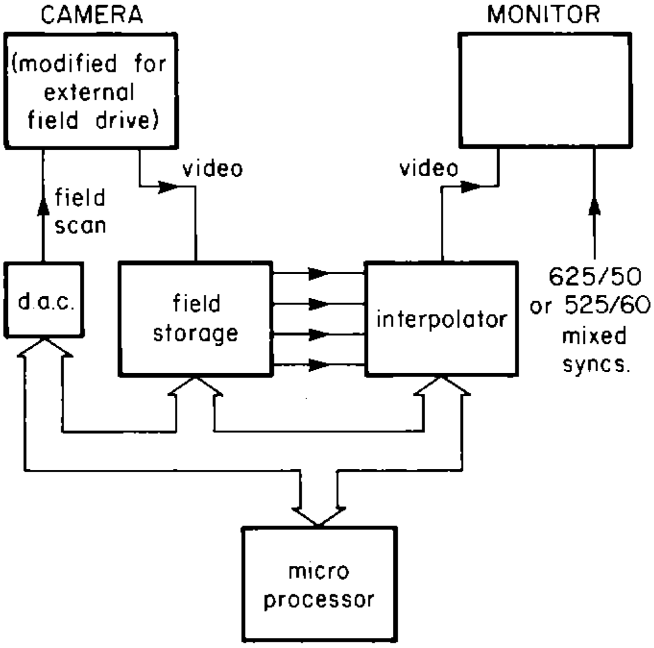


Fig. 1 - Block diagram of simulation equipment

The television camera used was a Philips PC60. This was one of the first colour cameras manufactured in Europe. Designed in the early 1960's, it employed the three tube principle, with one tube for each of the red, green and blue signals. Each tube was a 30 mm Plumbicon, which allowed the camera to attain a very respectable performance, despite its age. The camera was modified to take in an external ramp waveform to drive its field scans at any field rate and with any reasonable interlace ratio. In order to provide this degree of flexibility, the external waveform was generated by a high-speed microprocessor, via a digital-to-analogue converter (d.a.c.).

The output from the modified camera could be displayed directly on a monitor, similarly modified and fed with the same external field scanning waveform; when used, this simulated the performance of the HDTV signal in its own right. Alternatively the camera video could be fed to an array of field stores and an associated four-tap interpolator which could convert the signal to standard 625- or 525-line form. The addressing of the write and read areas of the field stores, and the coefficients used in the interpolator, were controlled by the same microprocessor as was used to generate the field scan waveform. The only constraint on the system was that it had to operate at a fixed line scanning speed (15.625 kHz when fed with 625/50 synchronising pulses, 15.750 kHz when fed with 525/60 sychronising pulses). Only video from the green tube was stored, being treated thereafter as a luminance signal, bandwidth limited to 5.0 MHz, so as to simplify the signal processing circuitry. This also removed the need to re-optimise the camera registration at every change of field rate.

The only compromise that had to be made was that, as the field rate was raised or interlace abolished, fewer lines per field could be displayed; if the pitch of the lines was kept constant, this inevitably meant that the height of the television pictures had to be reduced. For example, the camera could scan only 521 lines at a field frequency of 60Hz; this could then be taken as approximately 46% of the height of an 1125-line picture.

2.1 The Picture Material

In order to give repeatable results, especially between different sessions of the same sequence of subjective tests, it was necessary to have picture material which reproduced repeatably the full range of material normally televised. As well as requiring this material to exploit the full signal range in amplitude as well as in spatial frequency, it was also necessary to have a variety of predictable movement conditions so that the levels of artefacts produced by television processing could be adequately explored. In order to achieve this goal, two standard test objects were developed.

(i) a drum rotating around a vertical axis, around the outside of which was pasted a town scene from an '00' gauge model railway set. The drum was over a metre in diameter so that when the height of a house filled half the picture height, the depth of field of the lens for a typical studio shot ensured that a substantial portion of the width of the picture was near planar and in focus. The overall impression of motion was that of a sustained horizontal pan. An electronic control system was used to govern the speed of the motor driving the drum and this allowed pan speeds to be reliably obtained over a wide range, extending from below 0.1 to greater than 1.0 picture widths per second.

(ii) a disk rotating around a horizontal axis. The surface of the disk was matt black. Around the rim were pasted detailed pictures and graphic artwork. By focusing on a segment of the disk, it was possible to include both vertical and horizontal motion.

A picture of the experimental camera system, including these picture sources, is shown in Fig.2.

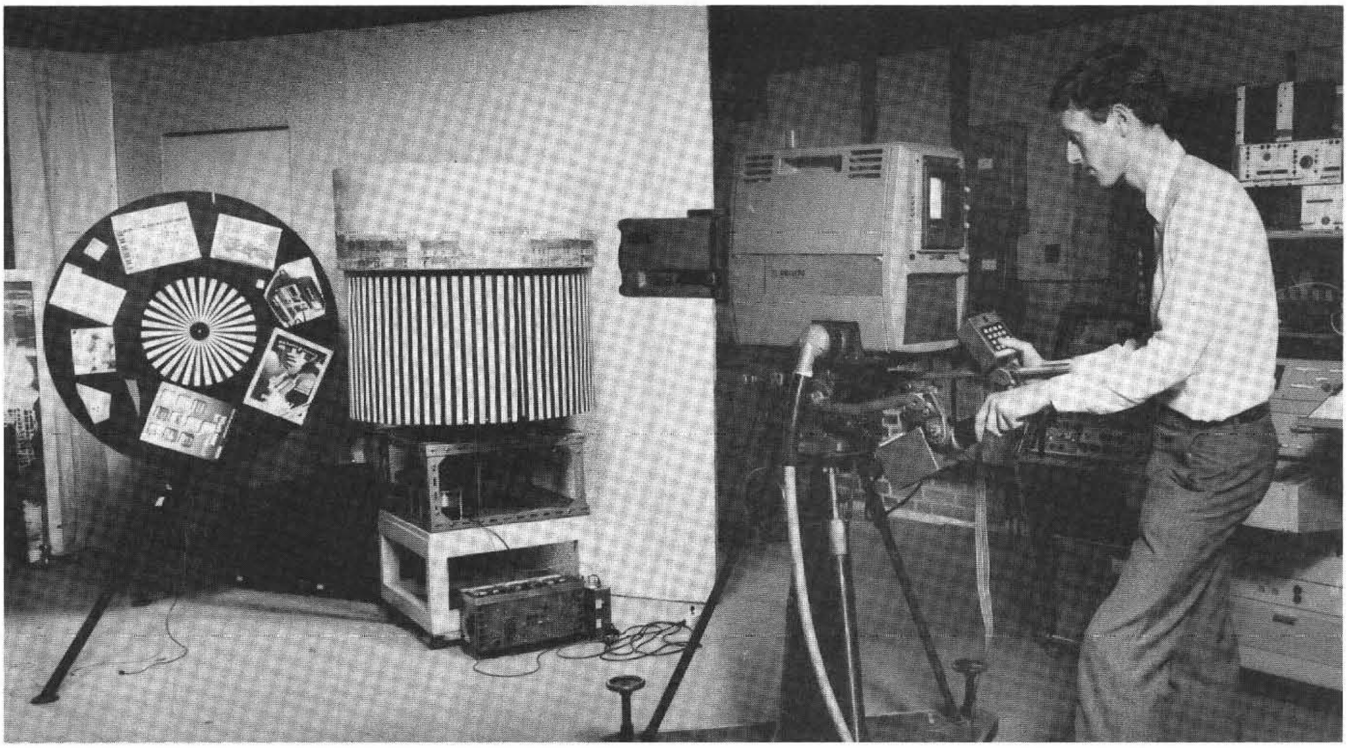


Fig. 2 - The modified camera and picture sources

3. FACTORS TO BE INVESTIGATED

3.1 The Effects of Interlaced Scanning

Although one of the main applications of the equipment has been to study the problems associated with field rate conversion of HDTV signals, this has not been the only factor investigated. Because of its implications to the other aspects of the work, it is convenient in this Report to consider one of these other factors first - that is the effect produced by the choice of either interlaced or sequential scanning in the camera (the choice of either interlaced or sequential scanning in the display has been considered in an earlier Report[3]).

Interlace was originally conceived of as a low cost bandwidth reduction scheme in the 1930's. Whilst it offers advantages, it does present difficulties in post production; that is, downstream manipulation. At its inception these difficulties were foreseen, but were regarded as an acceptable compromise[5].

An analysis of the implications of interlaced scanning in a television camera is not easy. The television image is sensed as a pattern of electrical charge on the target of a camera tube. This pattern is then read out by the scanning electron beam to form the output video signal. However, in interlaced scanning, a picture element on one field is not revisited by the beam until after a whole picture period, that is, until after the second, interlaced field has been read out. In theory, the erasure of one set of field lines should not affect the charge stored on the interleaved lines of the second field. In practice, however, the situation is not nearly so clear-cut. The scanning electron beam in the camera tube is attracted to the target by an accelerating mesh close to the light sensitive layer.

Having passed through this mesh, electrons are only weakly attracted to the target surface since only a small positive charge has integrated on it, the surface having previously been discharged to the cathode potential. The electron beam landing velocity is thus very low, so that the Gaussian cross-section profile can be modified or 'pulled' by locally integrated charge, the amount of pulling depending on picture detail. When trying to read interlaced lines, the beam may therefore be deformed to discharge adjacent picture lines which themselves have integrated for only 20 ms (one field period)[6,7].

Evidence that this is happening is provided by measurements of camera tube lag, which show that only 5% of the charge on the target remains after readout of the first field.

In order to confirm this hypothesis, the camera was programmed to scan at standards of 625/50/2:1, 625/50/1:1 and 625/25/1:1 (in this Report, the notation '1:1' will be used for sequential scanning standards and '2:1' for conventional 2:1 interlaced standards). Visual inspection of the motion portrayal of these three standards confirmed that the motion performance of 625/50/2:1 was similar to that of 625/50/1:1. Since the integration time of 625/50/1:1 must be 20 ms (the charge accumulated on each line is erased on every field), this confirms that the integration time for 625/50/2:1 is also 20 ms. In contrast, the motion portrayal of 625/25/1:1, which genuinely has an integration time of 40 ms, was extremely poor; severe smearing and lag was produced on even slowly moving objects. Thus it may be concluded that the predominant integration time of interlaced scanning standards is the field, and not the picture, period.

3.1.1 Implications of interlace on vertical resolution

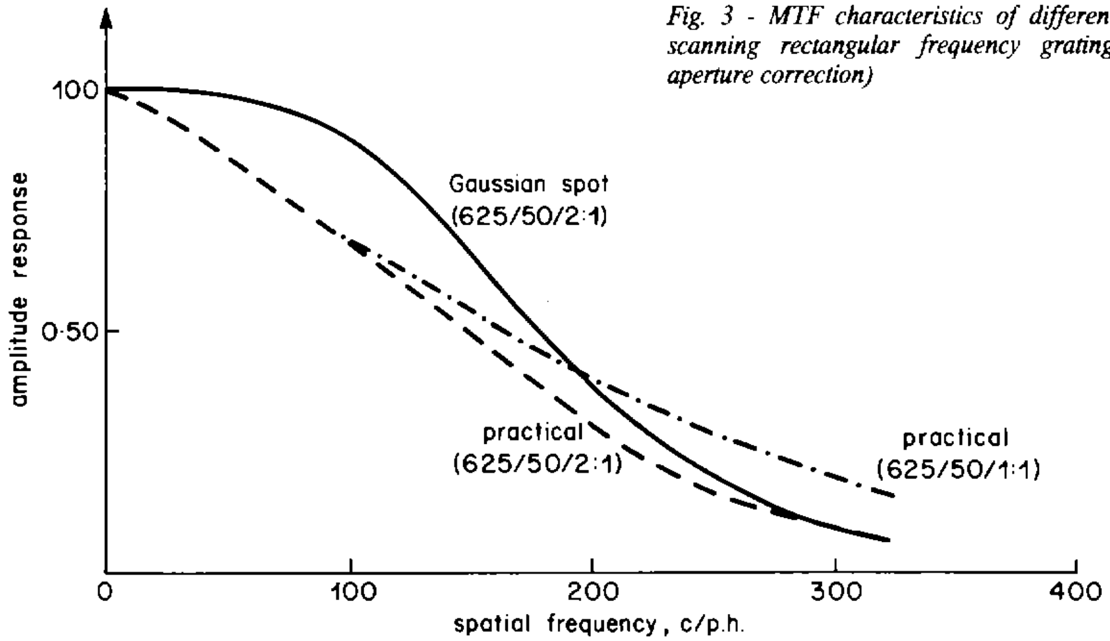
The results of the previous section show that, in reading out the lines of one field, the second interlaced field is also erased. This implies that each scan line of the camera target is actually wider than 1/625th of a picture height. Such a tendency for the camera spot to grow or shrink in order to match the scanning standard is relatively well-known[6,7]; it might, for example, be predicted that a sequential standard with 625 lines would allow a higher vertical resolution to be achieved than an interlaced standard with the same total number of lines, because of the higher number of lines on each individual field.

In order to quantify the degree to which this effect, known as 'self-sharpening', might occur, the vertical modulation transfer function of the combined lens and tube optical system was measured using an interlaced (625/50/2:1) and a sequential scan (625/50/1:1) with the same picture-line pitch. The amplitude responses obtained with such standards scanning square-wave frequency gratings are shown in Fig.3. Superimposed is the expected response had a Gaussian beam of 1½ picture lines half width scanned the same gratings. As can be seen, the beam shape has been heavily deformed from the commonly assumed model of a Gaussian spot. Furthermore, the sequential scan has a 6 dB better resolution than the interlaced scan, at the Nyquist limit (312.5 cycles per picture height (c.p.h.) for the 625-line scan considered here).

If a line-based aperture corrector is inserted in the video path, to compensate for resolution loss due to the camera optics and non-ideal scanning spot, the corrector boosts the sequential response where it is most needed, at half picture sampling frequency. With an interlaced scan however, since it has only 312.5 lines in a field, such an aperture corrector will only provide an improvement in resolution peaking at half the field vertical sampling frequency. At this frequency neither the interlaced nor the sequential scanning standard has suffered much attenuation. Thus it is difficult to provide an adequate compensation for the aperture losses of an interlaced scanning standard without over-correcting vertical frequencies around 156 cycles/picture height. A suitable setting for the aperture correction of a sequentially-scanned camera is, however, much easier to achieve. When this factor is taken into consideration, along with the improved resolution obtainable from the camera tube itself, the vertical resolution obtainable from a sequentially-scanned camera is seen to be considerably improved over that obtainable from an interlaced camera, in spite of the necessary 2:1 increase in bandwidth.

One possible advantage of interlace, however, is that, on static pictures, the extra number of lines effectively hypersamples the picture, thus reducing the likelihood of static vertical aliasing, as would be the case with a lower line number, sequential scan. However, vertical aliasing in a sequential scan can be regarded as a 'self-alias'; that is, a spatial alias 'folds back' as a spatial alias, as met in insufficiently pre-filtered one-dimensional sampling. In interlaced scanning, a spatial alias folds back as a temporal alias, as can be seen in Fig.4. This is a plot of the vertical-temporal energy content of a typical television signal.

Fig. 3 - MTF characteristics of different beam profiles scanning rectangular frequency gratings (no vertical aperture correction)



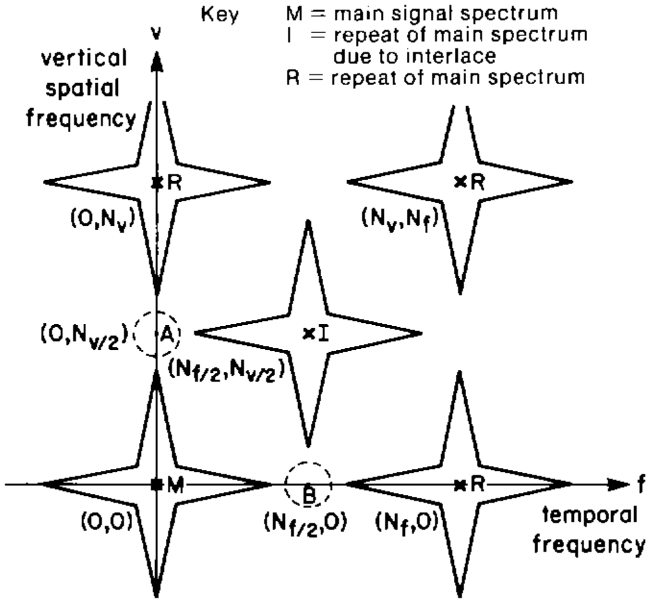


Fig. 4 - The repeat spectra of a typical television scan

Picture signal energy primarily occupies the star regions of the repeated spectra. Fine static vertical detail existing in area B of the interlace repeat spectrum I, (originating from area A of main spectrum M) is confused by the eye/brain as being low vertical frequency, high temporal frequency from the main spectrum M. Conversely, coarse vertical, high temporal frequency components may be confused as being fine static or near static vertical detail. Such 'cross-aliasing', where a spatial alias is transformed into a temporal alias, is subjectively more visible than self-aliasing and harder to interpret or correct; this can be seen in other forms of cross-aliasing such as the well known PAL 'cross-colour'. It is interesting to note that Kell and his colleagues[5] foresaw this deficiency of interlace, but, given the 'soft' sources and displays of the day, the regions A and B were infrequently excited. With improvements in technology, these regions are more frequently excited, showing up the deficiencies. Interlace is therefore a very efficient form of bandwidth reduction at the inception of a standard but improved equipment will later reveal its flaws.

3.2 The Effects of Field Frequency

In order to give the viewer a sense of continuous smooth motion, a picture sampling rate has to be decided upon. The early workers in the field[8] found that as few as 15 pictures per second could achieve this end. Later references[9] give a slightly higher figure at 25 frames per second.

Such low picture rates cannot, however, be used in television receivers since they would produce high levels of brightness flicker; the resulting pictures would be unwatchable at current display brightnesses without further processing in the display. Also, these picture rates would produce far too jerky motion in slow motion replay. Various researchers have published curves of full field brightness versus repetition rate in an attempt to measure the eye's response to flicker. No two results closely agree, but what is apparent is that:

(i) the ability to perceive flicker varies to some extent from person to person, as well as being dependent on the age of the observer.

(ii) the line of brightness of just perceptible flicker frequency increases approximately linearly when plotted against logarithmic intensity.

(iii) the just perceptible flicker frequency increases as the light pulses are made shorter.

(iv) as the angular subtense of the display is increased at the observer, more of the display is imaged on the retina in peripheral vision; this is more sensitive to flicker than central vision.

The brightest displays postulated in the future will have a peak brightness of 200-500 cd/m^2. A display rate of at least 70-75 Hz is consequently necessary in order to eliminate flicker substantially. Such a rate is well in excess of the threshold required to give smooth motion portrayal.

As well as giving a sense of smooth motion, however, the field frequency is also a major factor in determining the resolution of moving objects. To date, it has only been possible to have an integration, or exposure, period in a television camera equal to the time between successive visits of the electron beam to the same elemental area of the target. This meant that the integration period was fixed as the reciprocal of the field rate. Calculatons show that under such conditions, even for moderate motion speeds, dynamic resolution rapidly tails off. More recently, however, a camera based on the use of CCD area arrays has been introduced which contains an integral shutter, allowing the integration time to be reduced without increasing the field rate[10]. Film cameras, which use frame rates of 24 or 25 per second have long used shutters in order to allow time for the film to travel through the gate between exposures. This approach gives sharper movement on each frame, but at the same time increases the level of temporal aliasing in the film sequence.

As discussed in Section 2, however, it is not only important for the motion portrayal of the scanning standard to be good in its own right, but it is also necessary that standards conversion to the existing 525/60/2:1 or 625/50/2:1 terrestrial television standards should be possible with acceptable picture quality. A further aspect of the ability to undergo standards conversion is that it should be possible to record the HDTV signal on motion picture film, running at a speed of 24 or 25 frames per second, with acceptable quality. These factors, conversion to 525/60 and 625/50, conversion to film, effects of integration time on moving detail and the effects of shuttering an electronic camera, will each be considered in the following sections.

3.2.1 Conversion from different field frequencies to 625/50 and 525/60

Due to the rectangular integration period in cameras, the temporal frequency response is a sinc function. Such a function is a not very efficient form of low pass filter. Consequently, in any moving television picture, there are substantial amounts of temporal aliasing, which are coherent with the source field rate. When converted to another field rate, these aliases appear incoherently, offset in frequency by the difference between harmonic multiples of the input and output field rates. This is apparent in the 10 Hz judder predominantly visible at the output of standards converters such as 'ACE'.[11]

When choosing a field rate for a new HDTV standard, consideration must be given to the need to convert the standard to existing terrestrial standards. At the same time, however, if an HDTV standard is long-lived, it will outlive existing standards and, therefore, future use of the standard should not be unrealistically prejudiced.

There are two courses of action available in making this choice:

(i) choose a field rate harmonically related to one of the existing standards or

(ii) choose a compromise field rate that converts with a lower level of impairment to both European (50 Hz), and American (60 Hz) standards. Factors affecting this compromise choice are the amplitude and the frequency of any impairment.

In order to investigate the second of these options, the camera was operated over a range of field frequencies between 50 Hz and 100 Hz in order to establish whether a compromise field rate might exist[12]. The most likely candidate was a field rate of 80 Hz, since this produces a judder frequency of 20 Hz after conversion to both 50 and 60 Hz; departure from 80 Hz in either direction could be expected to worsen the conversion quality to one conventional field rate, while improving the quality of conversion to the other.

Such a compromise field rate can, however, only be acceptable if the conversion quality is sufficiently high in each case. In order to evaluate this conversion quality, therefore, two series of formal subjective tests were carried out. The first series investigated the impairments produced by conversion to 625/50; twenty-nine different observers, skilled in the assessment of television pictures, were used viewing at distances of 4H and 6H. Three scanning standards were investigated:

(i) 50 fields/sec without temporal interpolation.

(ii) 60 fields/sec with one temporal interpolation aperture.

(iii) 80 fields/sec with three different temporal interpolation apertures.

Sequential scanning was used for all three standards in order to ensure that only temporal effects were considered. The scan-line pitch was kept constant and blanking applied to the converted signal to maintain a constant displayed picture height regardless of camera field-rate. The displayed picture, therefore, comprised a rectangular window of approximately one quarter picture height, there being no static information which might reveal the input scanning standard to the viewer during the subjective tests.

The interpolator used contributions from four input fields. The three 80 Hz interpolating apertures were chosen to provide different frequency characteristics. One (designated 'soft' in the results described below) produced blurring on motion but little judder, another (designated 'medium') attempted to compromise between blurring and judder, whilst the third aperture (designated 'hard') produced good dynamic resolution at the expense of increased judder. The aperture designated 'medium' and the 60 Hz aperture were loosely modelled on the temporal aperture of 'ACE', the 4-field standards converter developed by the BBC for 625/50 and 525/60 cross conversion and manufactured under licence by GEC McMichael.*[11]

Only one interpolation aperture was assessed for conversion from 60 Hz as previous tests had shown this to be the optimum aperture for all motion speeds. Three apertures were assessed for conversion from 80 Hz since an optimum aperture had yet to be established for this standard.

Five conditions of motion were used in the tests:

(i) slow speed drum : horizontal transit time 4.7 seconds/picture width.

(ii) medium speed drum : horizontal transit time 2.8 seconds/picture width.

(iii) fast speed drum : horizontal transit time 2.0 seconds/picture width.

(iv) slow speed wheel : horizontal transit times: top : 3.6 seconds/picture width; bottom : 4.5 seconds/picture width.

(v) medium speed wheel : horizontal transit times: top : 1.8 seconds/picture width; bottom : 2.2 seconds/picture width.

A single stimulus method was used. For each condition a 10-second sequence of moving pictures was followed by a 5-second voting period during which mid-grey was displayed. Voters used the CCIR 5-point quality scale. A random sequence of conditions was presented; this sequence included frequent cross-checks to measure the coherence of response of the observers.

The results of this first series of tests are shown in Fig. 5. At the slower motion speeds the conversion of 80 Hz was judged as virtually transparent. As the speeds increased, 80 Hz was no longer capable of being converted transparently, but the quality after conversion was nevertheless judged as being substantially better than that of the best present-day 525-to-625 converters. It is worth noting that, at these high motion speeds, the loss of detail on the directly-generated 50 Hz picture due to camera integration was very apparent.

A second series of subjective tests investigated the level of conversion quality to 525/60. Again, three scanning standards were investigated:

(i) 60 fields/sec 1:1 without temporal interpolation.

(ii) 50 fields/sec 1:1 with three different temporal interpolation apertures.

(iii) 80 fields/sec 1:1 with three different temporal interpolation apertures.

As before, the interpolator used contributions from all four input fields. The three 50 Hz and the three

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* Now Marconi Communications.

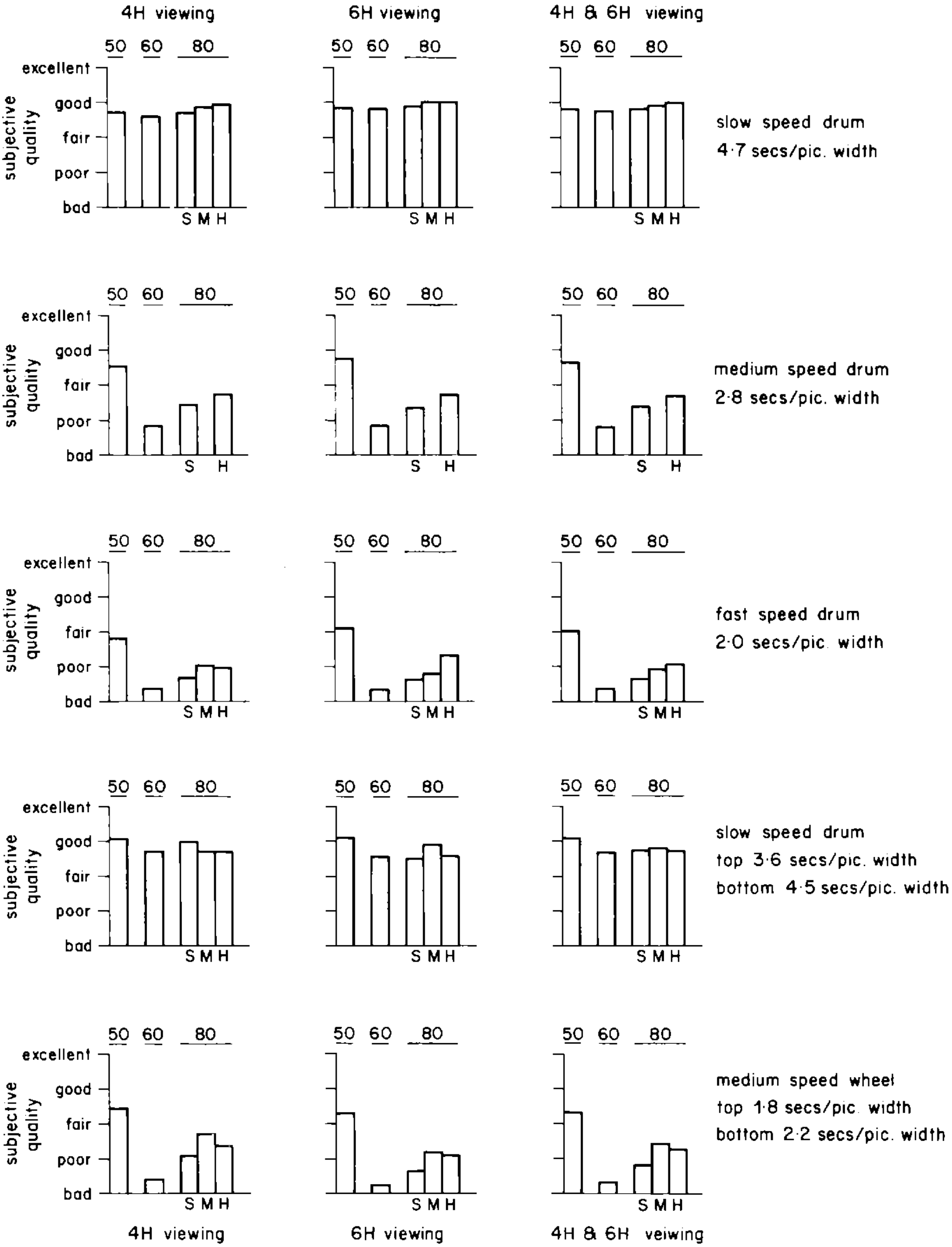

Fig. 5 - Results of subjective tests on conversion from possible HDTV field rates to 50 Hz/2:1

80 Hz interpolation apertures were chosen to provide different frequency characteristics, along the lines of those investigated for the 80/50 conversion tests. Since the conversion artefacts are most visible at higher speeds, and in order to reduce the number of items that had to be judged, the lower speed conditions of the first series were omitted and thus only three motion conditions were used:

(1) medium speed drum : horizontal transit time 2.8 seconds/picture width.

(2) fast speed drum : horizontal transit time 2.0 seconds/picture width.

(3) medium speed wheel : horizontal transit times top : 1.8 seconds/picture width; bottom: 2.2 seconds/picture width.

Twenty-five different observers, skilled in the assessment of television pictures, were used at viewing distances of 4H and 6H. The single stimulus method and 5-point quality scale of the first series of tests were retained but the sequence duration and voting period were increased to 20 and 10 seconds respectively as some observers had commented on the curtness of the previous test durations. The results of this second series of tests are shown in Fig. 6. They are similar to those of the first series in that they show that the use of an 80 Hz field rate for the studio standard yields a very significantly better quality of signal after conversion to 525/60 than would be obtained by the choice of 50 Hz for an HDTV field rate. As before, the 80/60 conversion did not provide a transparent level of quality; the degradation was, however, rather less than produced by 80/50 conversion, most likely due to the fact that the higher field rate of 525/60 can contain more unaliased temporal information.

3.2.2 Conversion from different field frequencies to motion-picture film

One of the prime application areas seen for HDTV is that of electronic cinematography, where electronically generated material may be recorded on to 35 mm motion picture film for general

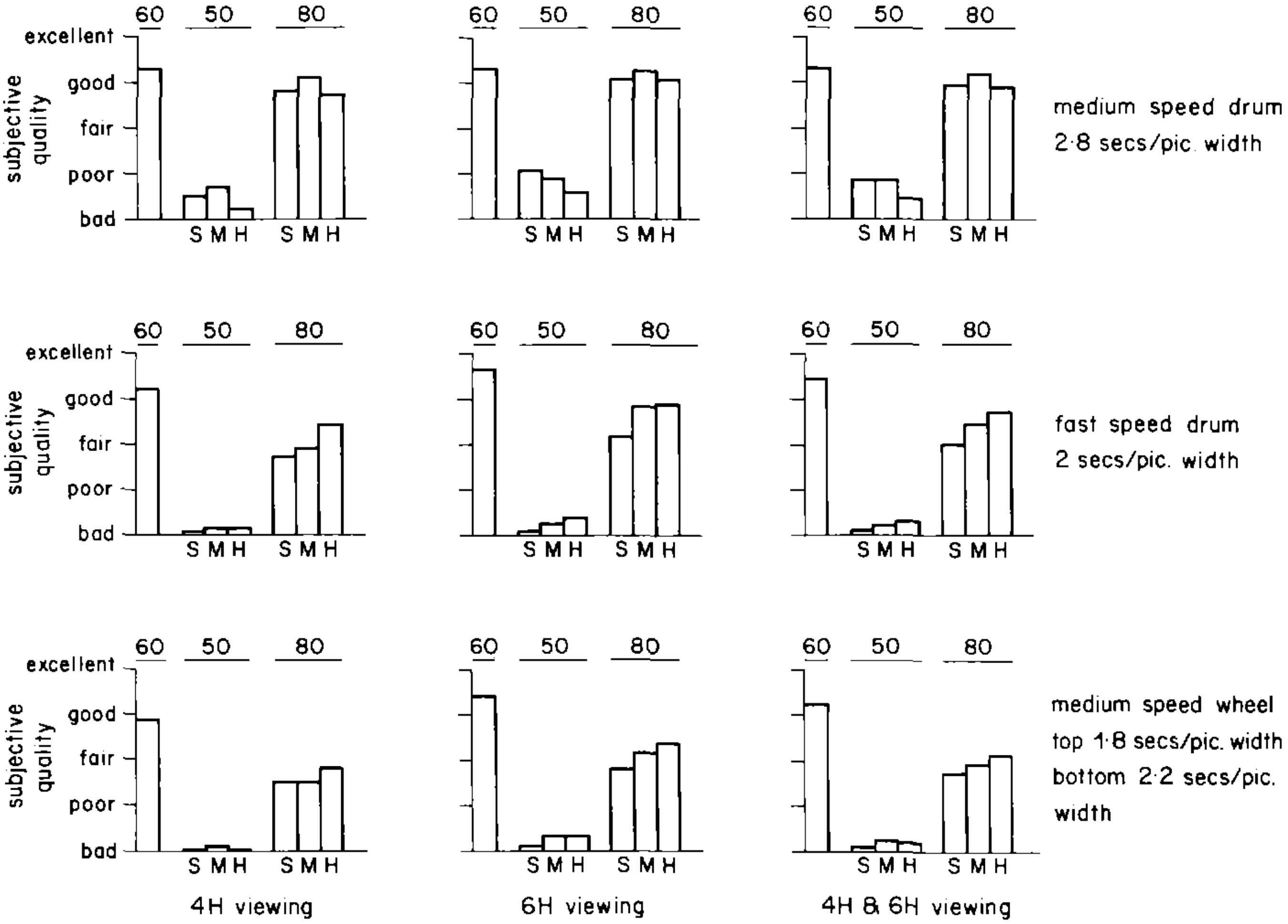

Fig. 6 - Results of subjective tests on conversion from possible HDTV field rates to 60 Hz/2:1

distribution. The quality achievable in this transfer process is thus of considerable importance.

Conversions to and from film are free from the restriction of line standards interpolation, since the film image itself has no line structure. The principal problem is the possible presence of temporal judder at the beat frequency between the television rate and the nearest harmonic of the film frame rate. A further complication is that in a film camera all parts of the image are exposed at the same instant in time, whereas in a television camera the exposure period for the top of any given field is not the same as for the bottom of that field; conversions between film and TV standards thus, in principle, involve the need for interpolation characteristics that vary between the top and bottom of the image. Since this is undesirable, it is possible, with very little error, to ignore this slope in time of the television fields and to equate the film standard with a sequentially-scanned structure; the conversion operations then become those of transforming a sequentially-scanned lattice at one field frequency to an interlaced lattice at a second field frequency, and vice-versa.

Ignoring, for the moment, the complications posed by the interlaced-to-sequential conversion, the main problem becomes once again that of field rate conversion. The film frame frequency used internationally for motion picture film is 24 Hz. However, it may be permissible to allow slight departures from this value. In Europe, film shown on television is almost invariably at the frame rate of 25 Hz, being an exact submultiple of the television field rate.

Possible field frequencies for the HDTV studio standard might be 50, 60 or 80 Hz, bearing in mind the results of the previous section. Of these three values, 50 Hz would be the simplest to instrument, with a fixed ratio of 2:1 between it and a slightly modified film frame rate of 25 Hz. The use of a 60 Hz field rate could be expected to produce a beat frequency judder on moving objects at a frequency of 12 Hz, while an 80 Hz field rate would give rise to a smaller amplitude of judder but at the more noticeable frequency of 8 Hz.

One possible way of overcoming the problems set by the choice of an 80 Hz field rate for the HDTV signal would be to record it onto film running at $26^2/_3$ frames per second rather than 24. The ratio between the field and frame rates then becomes exactly 3:1 and beat-frequency judder is eliminated. Such a film speed would only be 11% higher than standard and it may be relatively easy to modify film projectors in cinemas to cope with this change. The existence of two different film speeds could mean that cinema projectors must be capable of running at both 24 and $26^2/_3$ frames per second. Alternatively, adjustment of the projector to run at a compromise speed of $25^1/_3$ frames/sec would give an error of only 5% in each case. This would be very similar to the error routinely accepted in Europe, where films shot at 24 Hz are replayed at 25 Hz in order to lock the film rate to the television standard. Experience has shown that the penalties (a slight change in audio pitch of less than a semitone and an equivalent change in the duration of the film) are rarely noticeable. This solution might therefore be highly practical for the majority of cinemas.

Most film projectors use a 3-phase synchronous motor, coupled to the film transport system via a gear train. Conversion of the projectors could therefore be as simple as replacing a pair of gear wheels with a similar pair having a modified number of teeth.

Use of a compromise film speed would probably not be acceptable to the prestige, high-quality cinemas, however, and it is therefore necessary to determine whether or not dual-standard projectors could become available for these relatively few users. Several sets of replacement gears, while a practical possibility, are unlikely to be attractive. Probably the most practical method would be to use a high-power inverter to alter the frequency of the electrical supply to the projector motor. Such an inverter would need to be able to supply a significant amount of power — possibly up to 500 watts — but this is quite within the capabilities of modern equipment.

Some modifications were required to the simulation hardware of Fig. 1, in order to allow a practical investigation of these ideas. The modifications, shown in Fig.7, consisted of the addition of a second d.a.c. and associated interface to allow the modified monitor to be driven with a different field scan waveform to that used in the camera. The operation of a film projector was then simulated by driving the monitor with a sequential scan at either 72 Hz or 80 Hz field frequency, repeating each film frame thrice, thus mimicking the use of a triple-bladed shutter in conventional cinema film projectors. In contrast to the tests of the previous section, the camera was always scanned in an interlaced fashion since one of the main factors to be studied was whether conversion from an interlaced to a sequential structure was possible with adequate quality.

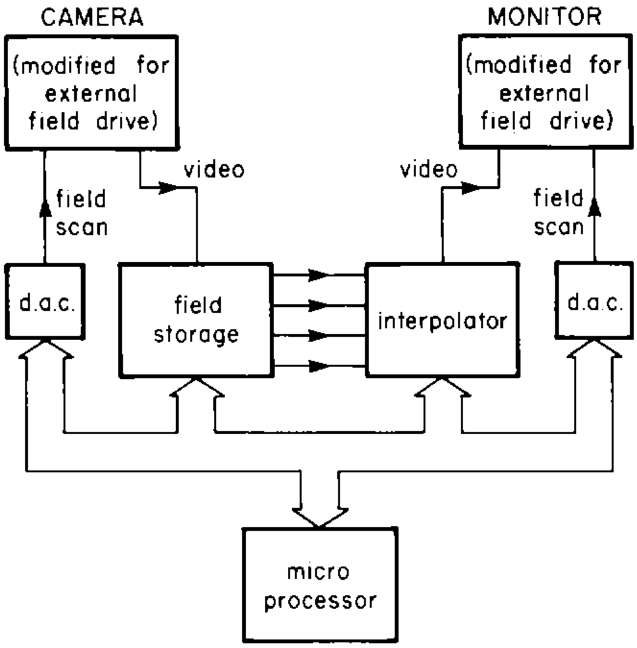

Fig. 7 - Block diagram of improved simulation equipment

As well as these 60 Hz and 80Hz interlaced scans, the camera was used to produce a 1/48th sec. exposure with sequential scanning, simulating a typical 24 f.p.s. film camera which could be used as a benchmark to compare its performance both against conventional film and as a measure of success of the conversions.

A wide variety of interpolation algorithms were assessed, ranging from those aimed at preserving the maximum amount of picture detail to those aimed at optimising the smoothness of picture motion, the two factors being interchangeable. In general, the algorithms designed to preserve picture detail did so by allowing significant levels of aliasing to remain on moving objects. This aliasing arose from an insufficient suppression of the interlace repeat spectrum of the input scanning structure and manifested itself as a 'combing' of horizontally moving edges. While it was not objectionable when observed directly, when resampled onto another interlaced structure employing the same picture line pitch, the possibility of multiple aliases becomes significant (see below). This approach fell foul of the idea of the clean video packet, outlined in the Introduction. Thus, later work tended to concentrate on the use of contributions spanning three picture lines vertically and three adjacent input fields in time, in order to minimise the level of aliasing on moving parts of the scene and remove any hallmarks of the interlaced structure of the input. Suitable compromises were found which performed well under all circumstances. Subjectively, the 8 Hz and 12 Hz judder components were found to be small, but did present a clouding of moving detail which was not apparent when a film frame rate of $26^{2}/_{3}$Hz was used in conjunction with an 80Hz HDTV standard. Of the arrangements simulated, this latter 'fast film' approach was preferred by experienced observers. Although moving detail was now somewhat softer than that of 24 frame per second film originated with a 1/48th sec. shutter, the frame rate judder associated with the display shuttering was markedly reduced. Overall this was judged to yield acceptable quality.

A second simulation was also carried out to investigate the telecine replay of such telerecorded film. The incoming HDTV signal was first formatted into 25 Hz sequentially-scanned pictures and each picture read out in two interlaced fields onto a standard 625/50 monitor. This highlighted the problem of multiple aliases identified above; all the combed areas, produced by algorithms designed to preserve the maximum detail, exhibited a pronounced low-frequency flickering which was very objectionable indeed. Algorithms based on the two-dimensional compromises needed to minimise aliasing were found to yield the best results; in this case the final level of quality achieved was very similar to that achieved in the simulation of optical projection.

3.2.3 The effect of field rate on integration time

The temporal response of a camera, that is its response to the reproduction of moving detail, is a function of the integration characteristic used to expose the light-sensitive layer as well as a function of the lag characteristic of the photoconductor. If, for a low lag photoconductor such as is used in plumbicon camera tubes, we ignore the lag effect, the integration aperture can be regarded as a rectangular period. The frequency domain transform is a 'sinc' function whose repeated zeros lie at multiples of the reciprocal of the integration period.

As the field rate is raised, so the integration time is shortened and the temporal response improved. In order to assess the potential for improving the quality of moving pictures by increasing the HDTV field rate, a further set of subjective tests was carried out. The camera was programmed to run at 50, 60, 70 or 80 sequential fields per second, thus producing integration periods of 1/50th., 1/60th., 1/70th., and 1/80th. second. The video so produced was displayed on the modified monitor after having been blanked top and bottom to maintain a constant displayed picture height regardless of field rate. The displayed picture, therefore, comprised a rectangular window of approximately one quarter picture height and there was no static information which might reveal the scanning standard to the viewer during the subjective tests. Nineteen experienced observers, viewing from 4H and 6H, took part in the tests, which used the same method and voting scale as in the second set of tests described in Section 3.2.1. Three conditions of motion were used:

(1) moderate speed drum : horizontal transit time 2 seconds/picture width.

(2) fast speed drum : horizontal transit time 1 second/picture width.

(3) fast speed wheel : horizontal transit times top : 1 second/picture width bottom : 1.2 second/picture width.

These motion speeds appear, at first sight, to be significantly higher than those used in previous subjective tests. However it should be borne in mind that, in contrast to the earlier tests, it is the performance of the HDTV system in its own right that was under assessment. Since the static horizontal resolution of HDTV is expected to be twice that of the modified 625-line camera and monitor used for the subjective tests, the display monitor can be regarded as a small window on a real display approximately twice the size, both vertically and horizontally. Consequently, the transit speeds become effectively:

(1) moderate speed drum : horizontal transit time 4 seconds/HDTV picture width.

(2) fast speed drum : horizontal transit time 2 seconds/HDTV picture width.

(3) fast speed wheel : horizontal transit times top : 2 seconds/HDTV picture width; bottom : 2.4 seconds/HDTV picture width.

and the equivalent viewing distances become 2.5H and 3.8H (after correction for an aspect ratio change from 4:3 to 5.3).

The results of the tests are shown in Fig. 8. They show that substantial improvements are obtainable by decreasing the integration time of HDTV cameras. For practical speeds, the subjective evaluation of motion quality starts to level out around a field rate of 70 to 80 Hz. At the highest motion speed tests however, the results demonstrate a preference for even higher field rates. Improvements of nearly 2 grades are achievable by moving from a 50 Hz field rate to one of 80 Hz.

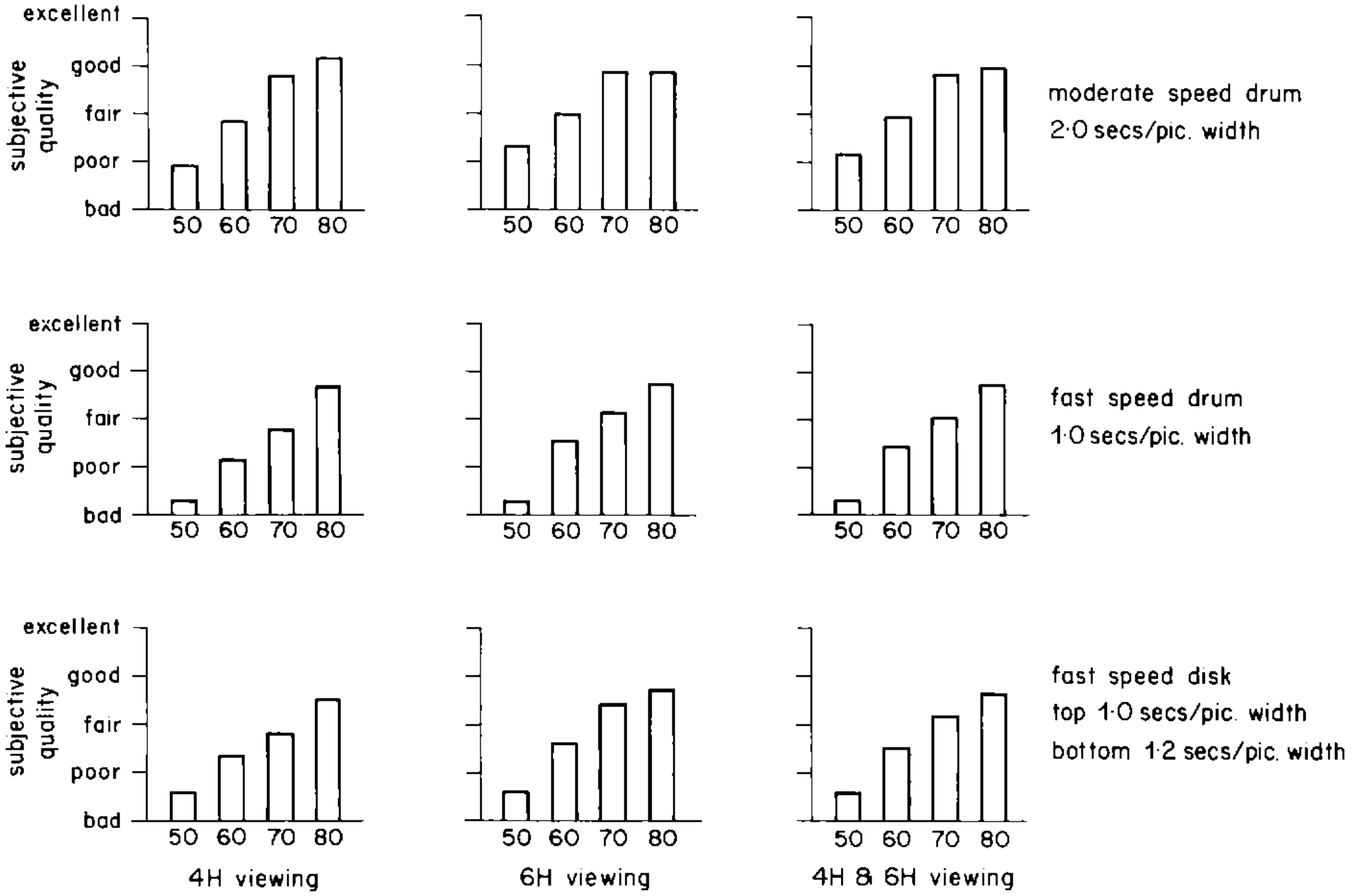

Fig. 8 - Results of subjective tests on HDTV temporal resolution for various field rates

3.2.4 The reduction of integration time by the use of an optical shutter

An alternative way of reducing the blur on moving objects caused by camera integration, that does not require an increase in field rate, would be to incorporate an optical shutter synchronised to the camera field scanning, which blanks out the light-sensitive area for a portion of the field period. Until recently, only in film cameras has such a shutter been commonplace. Using shutters in electronic signal sources would allow the field repetition rate to be dissociated from the exposure period necessary to give good motion protrayal; however such an approach increases the level of temporal aliasing present in the HDTV signal, which may produce other problems, as will be explained later.

It was not considered practical to add such a synchronised shutter to the modified camera. Instead a double scan technique was used; Fig. 9 shows the generalised field scan waveform for this technique. Using sequential scanning, and neglecting the errors due to photoconductive lag in the camera tube (estimated to be approximately 5%), the integration time for each portion of the camera tube target is simply the time since the scanning spot last visited that area. Thus the integration time for the portion AB of the scanning waveform is T_f - T_s, the integration time of the portion BC is T_s and the integration time of the portion CA is T_f. The use of integration times variable from zero to T_f can therefore be simulated by selecting only the portions AB or BC of the scan for display; it should be noted, however, at the extremes of this range, the usable portion of the field scan, and therefore the height of the final displayed picture, becomes very small. If T_s is made equal to $T_f/2$, the height of the final pictures is at a maximum. Since the exact duration of the shutter period was not critical in the experiments, it was decided to use this condition, $T_s = T_f/2$, so as to maximise the viewed area. It should be noted, though, that any value of $T_s$between about 0.35 T_f and about 0.65 T_f would have yielded practically acceptable viewing areas.

The camera was programmed to run at a 50 Hz field rate, with integration times of 1/50th or 1/100th second, or at a 60 Hz field rate, with integration times of 1/60th or 1/120th second. The output at the 60 Hz field rates was converted into a 625/50 signal using a four-field temporal interpolation algorithm, again loosely based on the 'ACE' converter.

A range of motion conditions were studied, using the rotating drum, although no formal subjective tests were carried out. The reduction of integration time was found to give a very worthwhile improvement in the motion quality of the 50 Hz signal, with no detectable judder. However the increased level of aliasing, responsible for the improved performance at the camera output, caused great difficulties in the conversion of the 60 Hz field rate signal to 625/50. Substantial levels of artefacts were produced on all but the slowest moving objects. Even when using a modified conversion algorithm, designed to minimise the level of aliasing at the expense of softening the moving resolution of the converted picture, acceptable results could not be obtained.

3.3 The Susceptibility of the HDTV Standard to Lighting Flicker

If the field frequency of the HDTV signal is

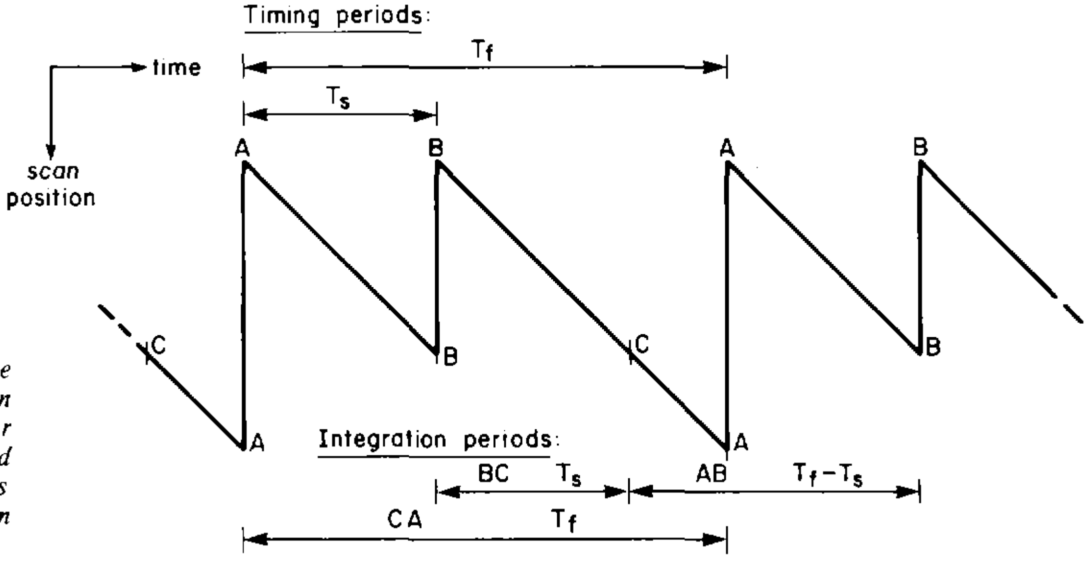

Fig. 9 - The double scan technique for obtaining reduced integration times in a television camera

substantially different from the mains power frequency, use of arc or fluorescent lamps can give rise to significant levels of lighting flicker. This is because the level of light produced by these light sources fluctuates as the instantaneous applied voltage changes through the cycle. Principally this occurs at even harmonics of the supply frequency due to symmetrical discharge from opposite electrodes in the light bulb on either half of the supply cycle. With ageing, or even from the time of manufacture, the electrodes may discharge unevenly on alternate half-cycles, leading to the generation of odd harmonics of the supply frequency, but usually at a low level relative to the even harmonics.

Although such lamps would normally be used in a multi-phase arrangement, with other lamps connected to other phases of the incoming mains supply, situations can arise when areas of the scene are predominantly lit from only one mains phase. The camera tube integrates the incident light for a field period. Fig. 10(a) shows how the total light integrated in each field varies as the field frequency beats with the frequency of the illumination variations.

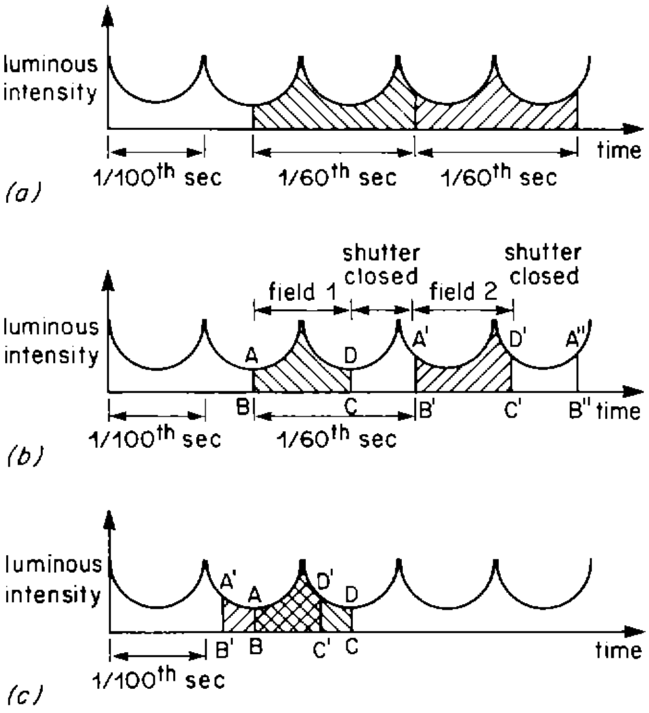

Fig. 10 - The typical flicker characteristic of an HMI discharge lamp, 50Hz supply frequency

The beat-frequency flicker is very similar to that which has been investigated in connection with the use of a film camera[13,14]. In that case the flicker could be controlled either by altering the film running speed or by adjusting the opening period of the camera shutter. If the possibility exists of using a shutter in an HDTV camera in order to improve its motion performance, it is of interest to investigate whether it can also help to remove lighting flicker.

Again, the field frequencies of interest in an HDTV shutter are 50,60 and 80 Hz. The use of a 50 Hz field frequency should be straightforward in the UK, since the mains power frequency is also 50 Hz. Thus lighting flicker will principally only be a problem with the 60 Hz and 80 Hz field rates. Cameras operating on these standards would be fitted with a shutter, whose frequency is locked to that of the field scanning waveform. If the time for which the shutter is open matches one cycle of the principal component of the illumination fluctuation (1/100th second in the UK), then the amount of light collected per field is constant. This is illustrated in Figs. 10 (b) and (c); the light collected during one field is marked by the area ABCD. The area A' B' C' D' illustrates the light collected in a following field. Fig. 10(c) shows these two areas redrawn so that they intercept the same cycle of the illumination fluctuation. Clearly the areas A B B' A' and D C C' D' are equal and therefore the areas ABCD and A' B' C' D' are also equal.

The use of a shutter could provide a total cure, therefore, for the even harmonic components of the illumination flicker on stationary scenes. A more sophisticated analysis shows that, even if the shutter takes some time to open and close, the flicker is still suppressed provided only that the temporal characteristics of the opening and closing periods match; this should be relatively easy to achieve in practice.

The operation of a synchronised shutter will be different depending on whether a conventional camera tube or a CCD area sensor is used as the pickup device in the camera. If a frame-transfer CCD is used, the integrated charges from all parts of the image detection area are moved together into the readout area during the frame transfer interval. Thus the times marking the start and end of each integration interval are coincident for all parts of the image sensing area. In consequence the shutter is made to cut off the incident light from all parts of the image sensing area before the frame transfer period and to ensure that the light is cut off until after this period has ended.

In a camera using conventional tubes, the integrated charge is read off as the electron beam scans each part of the target. Thus the start and end of each integration period varies from the top to the bottom of the image area. In this case the shutter should be made to pass across the face of the camera tube in synchronism with the scanning electron beam inside the tube.

Analysing the situation in terms of the camera's frequency domain response, the action of the shutter is to put repeated zeros in the response at multiples of the reciprocal of the shutter period. These repeated zeros can be placed at multiples of 100 Hz, which contribute the larger flicker power. Nothing can be achieved in this approach to remove the odd harmonics of supply frequency in the illumination. Also, when objects move, the lighting flicker components will be amplitude modulated to form sidebands around the supply harmonics. These will not be so effectively zeroed by the camera shutter.

In order to evaluate the magnitude of these effects, the camera was programmed to produce a 525/60/1:1 picture with either a 1/60th or a 1/100th second integration period using the techniques of the previous section. The camera imaged the drum being illuminated with an HMI discharge lamp powered from a single phase of the 50 Hz mains. As expected, gross flicker was present on the 1/60th sec integrated pictures. When the 1/100th sec integrated video was viewed, the flicker was substantially reduced. Slight flicker remained, however, largely due to instrumental imperfections and so it was not possible to judge accurately factors such as the level of lighting flicker at the odd harmonics of mains frequency (which are not reduced by this method), or the accuracy with which the shutter interval needs to track variations in the mains frequency. It was however possible to see the flicker return when the picture material moved; nevertheless this only became serious at speeds in excess of 2 seconds/picture width. Although this would scale to 4 seconds/picture width of the full HDTV resolution, it does give some encouragement for the final potential of flicker reduction systems.

4. CONCLUSIONS

A 625-line camera has been modified to allow external control of its field scan. The incorporation of field storage and interpolation has allowed a very flexible test bed to be produced. Whilst careful extrapolations will have to be made from the results, the need for this has been reduced by the ability to investigate a wide variety of parameters which will influence the choice of a suitable HDTV studio standard. Also studied was the quality that will result from the conversion of material produced in such a standard to present day 625/50 or 525/60 formats; in addition, conversion between HDTV video and 35mm motion-picture film was considered.

In particular it has been shown that there are many benefits in sequential (progressive) scanning being used in the camera. Such an approach does not preclude the conversion of the video to an interlaced form at a later stage in the signal chain. Secondly, a reduction in the integration period from that met in conventional television standards has been shown to offer significant improvements in motion portrayal. Such a reduction may be achieved either by an increase in the temporal sampling rate or by the use of an optical shutter in front of the image sensor - a technique that has long been used in the film industry but primarily for reasons other than improved motion portrayal. The use of this latter technique has to be exercised with caution however since processes downstream from the signal origination may be adversely affected. Another advantage in the use of shuttering is the possibility of substantially reducing the level of temporal aliasing of lighting flicker. If there is to be a single worldwide HDTV studio production standard it must be substantially unaffected by operation in regions where the power supply frequency is not a harmonic multiple of the television field rate.

Furthermore, it has been shown that by the choice of a compromise source field rate of 80 Hz it is possible to provide good conversion quality with little prejudice to the existing film or 50/60 Hz transmission formats. At the same time such a field rate provides an HDTV studio standard with the potential for improved motion portrayal. The main disadvantage of 80 Hz is, of course, the relatively high bandwidth and line scanning rate required by it in studio equipment.

5. REFERENCES

1. KUBO, T., 1982. Development of High Definition TV Display. IEEE Trans. Broadcasting, Vol. **BC-28** No. 2, June 1982. pp 51-64.

2. OHTANI, T., FUJIO, T. *and* HAMASAKI, T., 1976. Subjective evaluation of picture quality for future High Definition Television. NHK Technical Journal. Vol. 28 No. 4, 1976. pp 161-172.

3. ROBERTS, A., 1983. The improved display of 625-line television pictures. BBC Research Department Report No. BBC RD 1983/8.

4. HAYASHI, K., 1981. Research and Development on HDTV in Japan. SMPTE Journal, March 1981. pp 178-186.

5. KELL, R.D., BEDFORD, A.V. *and* TRAINER, M.A., 1936. Scanning Sequence and Repetition Rate of Television Images. Proc. IRE, Vol. 24, April 1936. pp 559-576.

6. KURASHIGE, M., 1982. Effect of self sharpening in low velocity electron beam scanning. IEEE Trans Electron Devices, Vol. **ED-29** No. 10, October 1982. pp 1570-1579.

7. KURASHIGE, M., 1983. Self sharpening effect on resolution in camera tubes. Journal of the Institution of Television Engineers of Japan. Vol. 37 No. 5, May 1983. pp 401-407.

8. KERKHOF, R. *and* WERNER, W., 1952. Television. Philips Technical Library, 1952. p 4.

9. ZWORYKIN, V.K. *and* MORTON, G.A. 1940. Television. J. Wiley and Sons Inc., New York, 2nd edition 1954. p 187.

10. GURLEY, T.M. *and* HASLETT, C.J., 1985. Resolution Considerations Using CCD Imagers in Broadcast Quality Cameras. SMPTE Journal, Vol. 94 No. 9, September 1985. pp 882-895.

11. CLARKE, C.K.P. *and* TANTON, N.E., 1984. Digital Standards Conversion : Interpolation Theory and Aperture Synthesis. BBC Research Department Report No. BBC RD 1984/20.

12. CHILDS, I. *and* ROBERTS, A.,1984. The Compatibility of HDTV Sources and Displays with present day TV Systems. Proceedings of the Tenth International Broadcasting Conference. Brighton, England. September 1984. pp 111-115.

13. TAYLOR, E.W., 1976. Some aspects of the use of metal halide discharge lamps for film lighting. BBC Research Department Report No. BBC RD 1976/2.

14. TAYLOR, E.W., 1977. Film lighting using metal halide lamps : some operating conditions giving freedom from picture luminance fluctuations. BBC Research Department Report No. BBC RD 1977/19.

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